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PHASE CALIBRATION OF A 2 BY 2 GPS ANTENNA ARRAY USING REAL AND SIMULATED GLOBAL POSITIONING SYSTEM (GPS) SIGNALS

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14. ABSTRACT
Software GPS receiver development has been undertaken. We are particularly interested in improving the GPS signal-to-noise/interference ratio using beam forming techniques. The phase relationship among the antenna array elements requires careful calibration. In this study, we will report a phase calibration technique for a 2 by 2 GPS antenna array using both simulated and real GPS signals. This technique is based on the GPS signal-processing algorithm developed for the software GPS receiver. A four-channel digital data collecting system was used in the experiment. For a simulated GPS signal, the experiment was conducted in an anechoic chamber in which a GPS simulation system was facilitated. For real GPS signals, we conducted the experiment on a rooftop to receive the signal from GPS satellites. The calibration verified the coherent nature of the signals among the elements. The results also allowed the source's direction to be determined.

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ABSTRACT

Software GPS receiver development has been undertaken. We are particularly interested in improving the GPS signal-to-noise/interference ratio using a beam forming techniques. The phase relationship among the antenna array elements requires careful calibration. In this study, we report a phase calibration technique for a 2 by 2 GPS antenna array using both simulated and real GPS signals. This technique is based on the GPS signal-processing algorithm developed for the software GPS receiver. A four-channel digital data collecting system was used in the experiment. For a simulated GPS signal, the experiment was conducted in an anechoic chamber in which a GPS simulation system was facilitated. For real GPS signals, we conducted the experiment on a rooftop to receive the signal from GPS satellites. The calibration verified the coherent nature of the signals among the elements. The results also allowed the source's direction to be determined.

Keywords: Antenna Measurements, Data Acquisition, Phased Array, and GPS

1. Introduction

GPS receiver development using a software approach has attracted interest lately. The development deviates from the conventional hardware approach which is usually limited by the functional performance of each individual component in the system. The software was implemented in a signal processing chip to perform flexible functions such as varying an A/D converter's sampling rate, implementing numerical filter and modulation schemes, optimization of the algorithm for enhancing signal to noise/interference ratio, etc [1]. This approach is particular attractive, since communication protocol, including GPS is in constant modification [2]. The current DSP chip and portable computer technologies have made the real time GPS receiver a reality. In fact, a real-time software GPS receiver has just been demonstrated [3].

Being a weak signal, GPS signals are vulnerable to interference sources. We are interested in improving the signal to noise/interference ratio of GPS signals using a beam-forming technique. The technique requires a multi-element antenna that serves as a phased array. The data received by each channel was treated as an input. A weighting vector operating on the input produces an output signal. Theoretically, the weighting vector can be formulated according to the desired output in order to place a lobe with a maximum gain in a certain direction, and place a null at others. This is feasible because of the fact that the signal received at the array is coherent. The verification of the coherent nature becomes essential for beam forming technology development.

In a previous study, we performed phase calibration of a 2 by 2 GPS antenna array which was mounted on two different ground planes. The probing beam was a right circular polarized (RCP) continuous wave (CW) at L1 frequency (1.57542 GHz). The result confirmed the coherent nature among the signals received at the four channels [4]. In this study, we performed phase calibration of the same 2 by 2 GPS antenna array using both simulated and real GPS signals. The experiment using simulated GPS signal was conducted in an anechoic chamber. The experiment using real GPS signal was conducted on a rooftop of a building. The received signals were processed using computer codes developed for a software GPS receiver. This method to measure phase was first validated by two simple experiments. One was to measure the phase velocity in a coaxial cable, and the other was to verify the right circular polarization characteristics of the GPS signals received from satellites. The phase relationship among the four channels was also used to calculate the direction of the sources. Reasonable results were obtained.

2. Experimental Set-up

1. A 2 by 2 Antenna Array

In the anechoic chamber, the 2 by 2 GPS antenna array was mounted in a large ground plane as shown in Fig, 1. The array was located in the chamber's quite zone on a three-axis positioner. RF cables were connected from the antenna to the GPS data acquisition system. This positioner allows a rotation with respect to the normal of the array plane and a tilting motion of the array plane. In front of the antenna array, there was an in-chamber GPS dome with a GPS constellation.

To conduct the real GPS signal experiment, the center disk where the 2 by 2 antenna array was mounted (as seen in Fig. 1) was placed on a tripod on a rooftop of a building. The signals from GPS satellites were received by the antenna array.

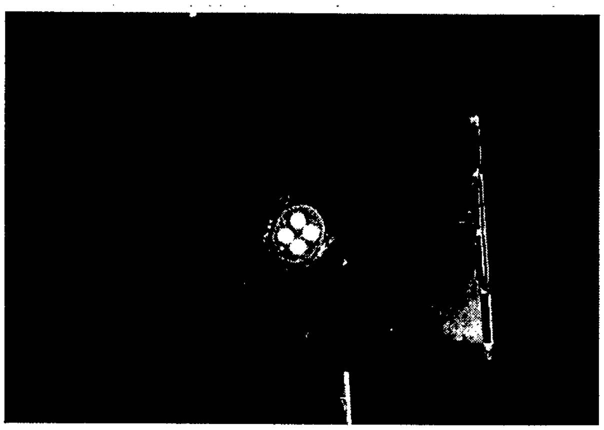

Fig. 1 The 2 by 2 GPS antenna array on a rolled-edge ground plane

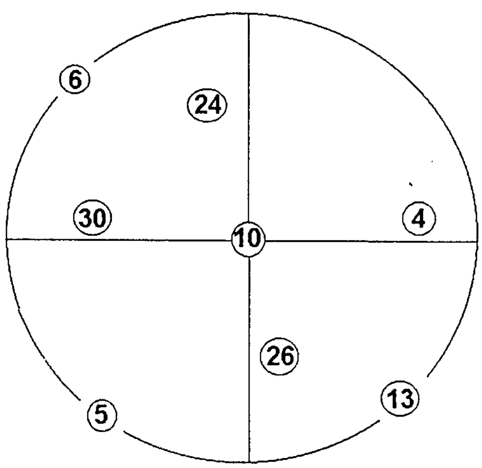

Fig. 2 The simulated GPS satellite constellation on the geodesic dome.

2. GPS Simulator

The GPS simulation facility consisted of a geodesic dome with a number of antennas mounted on it. These antennas were fed by a simulated GPS signal from a GPS signal simulator manufactured by Global Simulation System, Inc. The simulator can support up to 12 channels of GPS signals. The antennas mounted on the geodesic dome form a simulated GPS satellite constellation. Fig. 2 shows the simulated GPS constellation used in this study. There are 8 GPS satellites in the constellation. The number indicates the GPS satellite number. The one at the center of the dome (satellite number 10) corresponds to the zenith satellite above the phased array. The direction angle of the circumference from the normal of the array plane is about 45°.

The signal used in this experiment is RCP L1 C/A coded GPS signal. The source power level was set to a value so that the antenna received a slightly higher power level (-120 dbm) as it would receive from the GPS satellites when the receiver is on the Earth. (Normally GPS signal power is between –130 and –120 dbm on the Earth surface).

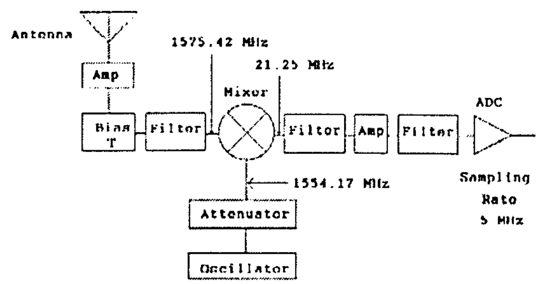

Fig. 3 The modular diagram of the GPS receiver.

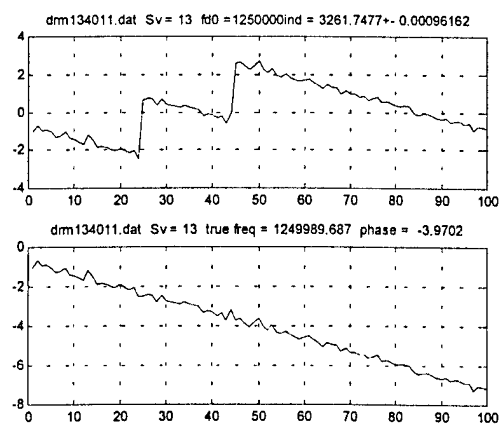

Fig. 4 A typical phase vs. time (in mini-second) results from the GPS acquisition algorithm.

3. Data Acquisition System

Fig. 3 shows a modular diagram of a one-channel GPS receiver [1]. The front-end antenna receives a microwave signal. This signal was amplified by a LNA. After a

bias-T and filter, the signal was down-converted to a frequency
of about 21.25 MHz (the difference is due to Doppler frequency shift). This signal was further amplified, and finally was digitized by an analog to digital converter (A/D) with a sampling rate of 5 M samples per second.

4. Signal processing algorithm

For each measurement, a 100-millisecond (ms) digitized signal was collected. The data exhibited an output frequency of about 1.25 MHz. Multiplying the measured data with a time series of $\exp(-j2\pi f_0 t)$, where f_0 is 1.25 MHz, results in a complex time series containing only the dc and $2f_0$ components. Taking the average out of every 5000 data points (i.e., a one millisecond-worth of data), only the dc component was left in the reduced-size complex time series. By plotting the phase for each millisecond of data, the frequency can be determined very accurately. With this analysis, a frequency uncertainty of less than 0.2 Hz was usually achieved. This is better than the resolution of 10 Hz, achieved by FFT of a 100ms data. The frequency accuracy can be further increased if data with a longer time were taken or a radiation source with a larger signal-to-noise ratio was used. A typical phase vs. time figure for a single channel is shown in Fig. 4. The Phase modulation due to the navigation data bit occurred at a 20 ms interval is clearly seen in the upper figure. It is removed in the lower one. By comparing the phase vs. time of the four elements, one can calculate the phase shift between the elements. This method using phase calibration rather than the correlation in the time domain is referred to as carrier phase-based method.

We can also determine the phase shift between two elements in the following way. Let $s_1(t)$ be the measured time series for element 1, and $s_2(t)$ for the element 2. Using the accurately determined frequency and the data processing scheme described previously, both time series are converted to the complex time series containing only the dc component. Then one performs the FFT operation of $s_2(t) \bullet s_1^*(t)$. The resulting dc component provides the phase shift between element 2 and element 1.

3. Theoretical Phase and Source Location Calculations

1. Phase Calculation

Fig. 5 shows schematics of the relative orientation of the antenna array and the GPS signal sources. The antenna array is on the E-N plane, and the source orbit is on E-N plane with a different Z. The phase shifts based on the electrical length difference can be calculated by the following equations:

$$\phi_2 - \phi_1 = k[(\sin\alpha\cos\beta\cos\delta + \sin\alpha\sin\beta\sin\delta) + (\sin\alpha\cos\beta\sin\delta - \sin\alpha\sin\beta\cos\delta)] + \delta\phi_{21}$$

$$\phi_3 - \phi_1 = k(-\sin\alpha\cos\beta\cos\delta - \sin\alpha\sin\beta\sin\delta) + (\sin\alpha\cos\beta\sin\delta - \sin\alpha\sin\beta\cos\delta)] + \delta\phi_{31}$$

$$\phi_4 - \phi_1 = k(\sin\alpha\cos\beta\sin\delta - \sin\alpha\sin\beta\cos\delta) + (\sin\alpha\cos\beta\sin\delta - \sin\alpha\sin\beta\cos\delta)] + \delta\phi_{41}$$

where $k = 2\pi d/\lambda$, d is the distance between the element and the center of the array, λ is the wavelength, $\delta\phi_{21}$, $\delta\phi_{31}$ and $\delta\phi_{41}$, are the internal phase shifts due to the RF paths between the antenna and the A/D in the signal chain, α is the inclination angle and $(\beta$-$\delta)$ is the rotation as defined in Fig. 5.

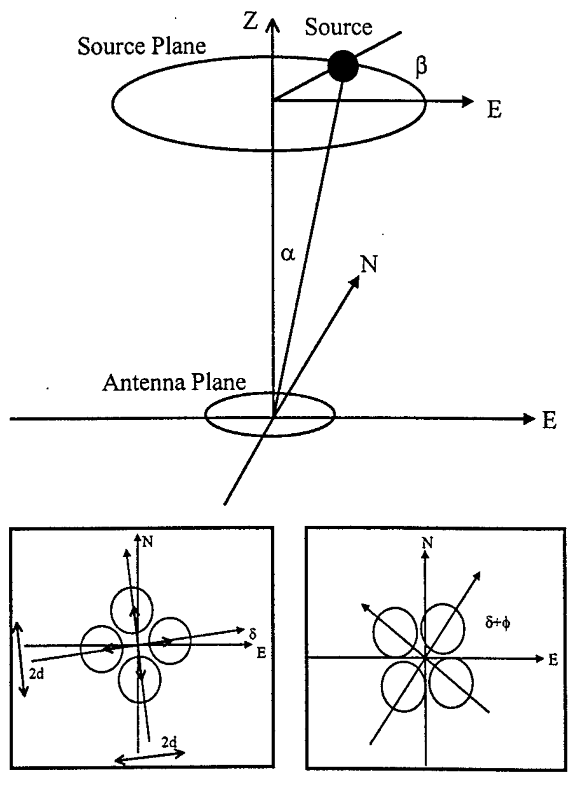

Fig. 5 A schematic phase array (E-N plane) and source positions.

2. Source Location Calculation

In order to determine the direction of the satellite sources, a number of measurements and a least-square-fit technique were used. These measurements were conducted with a number of settings of different rotation angles (shown in the bottom of Fig. 5). For the anechoic chamber scenario, there were seven rotation angles used (from 0° to 180° with an interval of 30°). Data was collected at each element for each setting, and the data was processed using the carrier phase-based method. Each setting results in three phase shifts (channel 1 is the reference channel). For each satellite source, there are thus, 21 equations (7 x 3) with 7 unknowns (α, β, d, δ, δ_{21}, δ_{31} and δ_{41}). A least-square-fit numerical technique was used to determine the unknowns, and thus the direction of the sources.

For the rooftop scenario, four rotation angles in the azimuthal plane were used (0°, 30°, 60° and 90°). Data was collected at each element for each setting and the data was processed using the same carrier phase-based method. For this case, to determine each visible satellite source, there are 12 equations (4 x 3) with the same 7 unknowns. The same least square fit numerical technique was used to determined these unknowns. Because of the reduced number of measurement, a larger uncertainty than those in the anechoic chamber measurements would be expected.

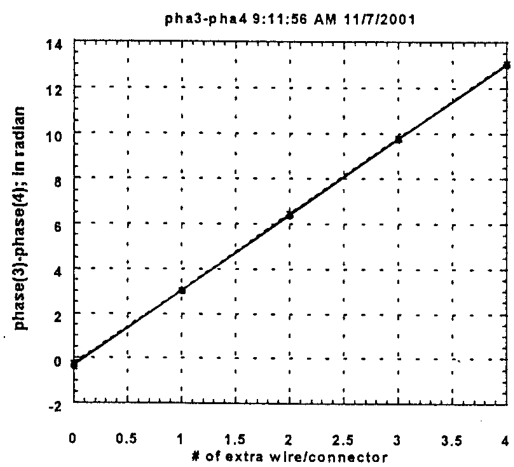

Fig. 6, The phase shift vs. # of section of RF coaxial cables.

4. Results and Discussion

1. Algorithm Verification

The GPS signal-processing algorithm has been verified using experiments with two scenarios. The first scenario was that an antenna received a real GPS signal from the satellites. The signal output was split into two branches. One of the branches has intentionally added more sections of RF coaxial cable with each section having a length of 31.5 cm. The phase relationship between these two branches was measured using the algorithm described. The results were shown in Fig. 6 as a function of the number of the added section. From this result, the phase velocity was calculated to be 66% of that of the speed of light, a result close to what was measured using a microwave network analyzer.

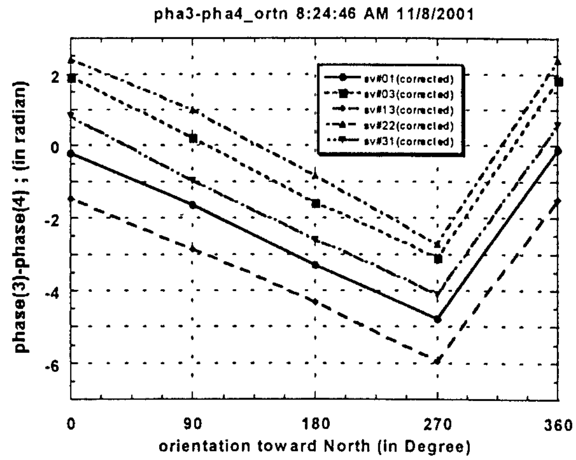

Fig. 7 Phase shift vs. relative orientation. Different curves are for different GPS satellite.

Another scenario was that GPS signals were measured using an array of two antennas. The orientation of the first antenna is fixed and the second one is rotating in the E-N plane. Therefore, these two antennas have a relative azimuthal orientation. If the received carrier is circular polarized, the phase delay should be revealed by this relative orientation. The phase relationship between these two antennas was measured using the method described. Fig. 7 shows the phase shift vs. the rotation angle of the second antenna. Each curve in the figure is for each visible GPS satellite. It shows that the difference in the phase shift is of the same amount as the angle that the second antenna rotated (in right circular direction). This result indicates the characteristics of a RCP wave.

2. GPS Simulation Results

The phase shift vs. rotation angle for the satellites 4 and 13 are shown in Figs. 8 and 9, respectively. Both the measurements and the calculation results are shown. The calculation was done using the best-fit values for those directional parameters in the phase calculation equation. Both results are in good agreement.

The directions of the satellites in the geodesic dome were determined using the method described in the previous section. The results are shown in Table I. The root-mean-square error indicates the quality of the fit between the measured data and the best fit curve. Though there was no direct geometrical measurement, the results seem to be in good agreement with the observation of the geodesic dome and the GPS simulated satellite setting (compare with Fig. 2).

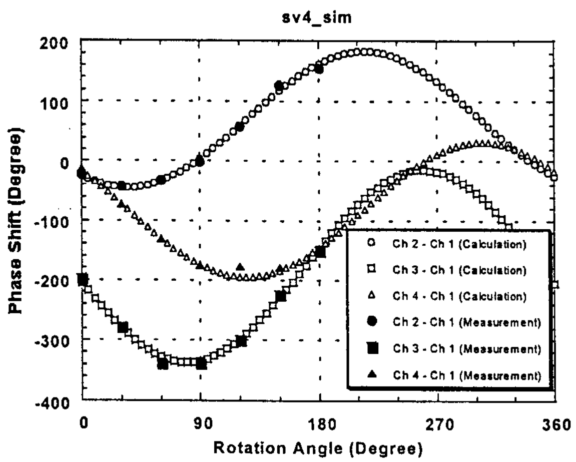

Fig. 8 The phase shift vs. rotation angle measured from the real GPS signal of satellite #4.

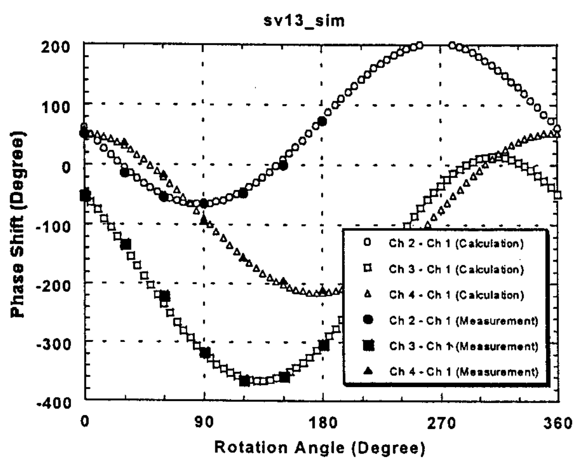

Fig. 9 The phase shift vs. rotation angle measured from the real GPS signal of satellite #13.

3. GPS Field Results

The real GPS signal data was taken on the rooftop of a building. The phase shift vs. rotation angle for the satellites 4 and 13 are shown in Figs. 10 and 11, respectively. Both the measured and the calculated results are shown. The calculation was done using the same method as in the previous sub-section. Table II shows the best-fit parameters for the direction of the GPS satellites. The satellites' directions measured by GPS Builder are also tabulated. The discrepancy between these two sets of data may be due to two reasons. One is the small number of measurement (12 equations to fit 7 unknowns) in the least-square-fit process resulting in a large uncertainty. The other is that it took about three minutes to complete the GPS data taking which involved manually rotating the 2 by 2 antenna disk. The locations of the GPS satellites were blurred during this time lapse. These may explain why the fitting for the real GPS data is less accurate than those for the GPS simulation data.

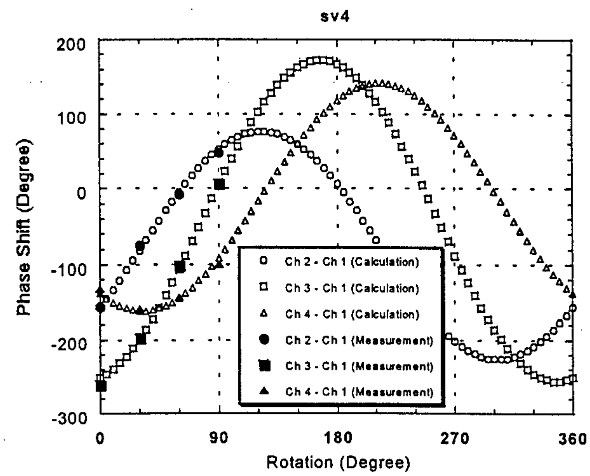

Fig. 10 The phase shift vs. rotation angle measured from the real GPS signal of satellite #4.

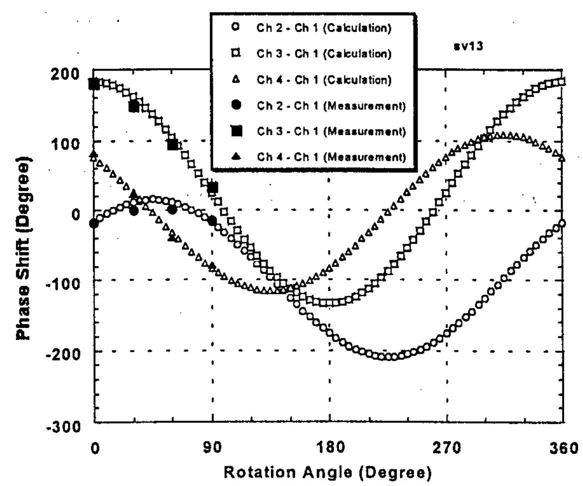

Fig. 11 The phase shift vs. rotation angle measured from the real GPS signal of satellite #13.

5. Summary

Phase calibration of a 2 by 2 GPS antenna array was conducted. Both simulated and real GPS signals were used as the probe beams. The array was connected to a four-channel GPS receiver. The simulated GPS experiments were conducted in a mid-sized anechoic chamber and the four-channel received signals from a simulated GPS satellite constellation. The real GPS experiments were conducted on a rooftop of a building to receive the signals from the GPS satellites. The software developed for a software GPS receiver was used to process the data. It provided the phase relationship among the four channels. The analytical phase calculation was derived. The measurements and the analytical results were in good agreement. Measurements of the phase shifts among the four channels with multiple settings of the antenna array were made. Using the best-fit technique, the directions of the sources could be determined. That method was demonstrated. The results presented here may lead to a further development of a beam forming technique to enhance signal to noise/interference ratio.

Table I, The best-fit parameters for the direction of the satellites in the simulated GPS constellation

Satellite #	Inclination Angle (degree)	Angle from East (Degree)	Root-Mean-Square-Error (Degree)
4	37.4	10.3	6.5
5	45.4	-112.5	4.1
6	40.1	134	5.1
10	1.57	27.9	1.9
13	45.9	-41.8	4.6
24	21.9	94.9	4.7
26	15.8	-85.4	2.7
30	25.8	172.4	4.3

Table II, The best-fit parameters for the direction of the GPS satellites using the received real GPS signals

Satellite#	Best-fit Inclination Angle (Degree)	Best-fit Angle-from-East (Degree)	GPS Builder's Inclination Angle (Degree)	GPS Builder's Angle-from-East(Degree)
4	50.4	77.5	59.7	66
7	33	-15.6	26.5	-29
20	66.2	174	66.7	169
28	15.4	173	14.4	167.5

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